

Injection of spin-polarized carriers from a ZnMnSe/CdSe semimagnetic superlattice into a non-magnetic ZnCdSe quantum well

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Abstract. We report on magneto-optical studies of spin injection from a ZnMnSe/CdSe semimagnetic short-period superlattice (SL) to a non-magnetic ZnCdSe quantum well (QW). The carriers are photo-generated in the semimagnetic SL, spin polarized via the effect of giant Zeeman splitting and then injected into the non-magnetic QW through a tunneling mechanism. Near 25% injection efficiency has been demonstrated at the magnetic field of 0.8 T and low temperature (1.8 K).

Recently there has been a growing interest in semiconductor devices based on precise manipulation of an electron spin rather than on controlling an electron charge [1]. Among the proposed device ideas are spin memory devices, spin transistors and spin quantum computers. For all such devices spin-polarized electron injection in semiconductor heterostructures is a necessary requirement. Until recently, the most successful realizations of the injection of spin-polarized electrons have implied the use of diluted magnetic semiconductors (DMS) [2–4]. Both II–VI semimagnetic semiconductors [2, 3] and III–V ferromagnetic semiconductors [4] were used to demonstrate efficient spin injection into a non-magnetic III–V semiconductor structure.

In this work we study the injection process of spin-polarized carriers from a ZnMnSe/CdSe semimagnetic short-period superlattice (SL) to a ZnCdSe/ZnSe non-magnetic quantum well (QW). The samples studied here are a modification of the structures containing a ZnSe/CdSe SL (with sub-monolayer (ML) CdSe insertions) and an attached ZnCdSe QW, whose transport and optical properties are known in detail [5]. Incorporation of a small amount of Mn in the SL barriers makes possible almost complete spin polarization of the miniband electrons and holes by an external magnetic field via the effect of giant Zeeman splitting [6] and allows magneto-optical investigations of the spin-polarized carrier injection into the non-magnetic QW.

Two samples studied in this work were grown by molecular beam epitaxy pseudomorphically on (001) GaAs substrates. They consist of a ten-period $Zn_{0.96}Mn_{0.04}Se$ (4nm)/CdSe (0.8 ML) DMS superlattice and an attached 7 nm thick $Zn_{0.75}Cd_{0.25}Se$ single QW (SQW) (the schematic drawing of the essential sample region is shown in Fig. 1). The first SL barrier adjoining the SQW is free of Mn, to avoid overlapping of the electron and hole wave functions in the non-magnetic QW with the DMS regions. The two samples differ in the thickness of the first ZnSe barrier. In sample A its thickness is enhanced a factor two as compared with other SL barriers (up to 8 nm). In sample B all SL barriers are 4 nm thick. The "SL+SQW" region is surrounded by thick $Zn_{0.93}S_{0.07}Se$ claddings lattice-matched to GaAs. Photoluminescence (PL) of the samples was measured in an external magnetic field up to 5 T in Faraday geometry at 1.8 K. Different linearly polarized lines of a cw Ar^+ laser

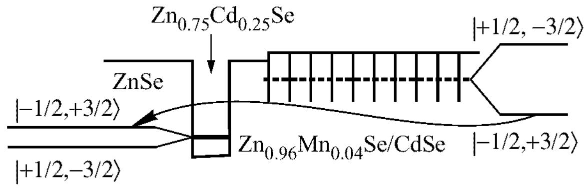

Fig. 1. Schematic drawing of the intrinsic region of the sample and a scheme of SQW and SL excitonic levels in a magnetic field.

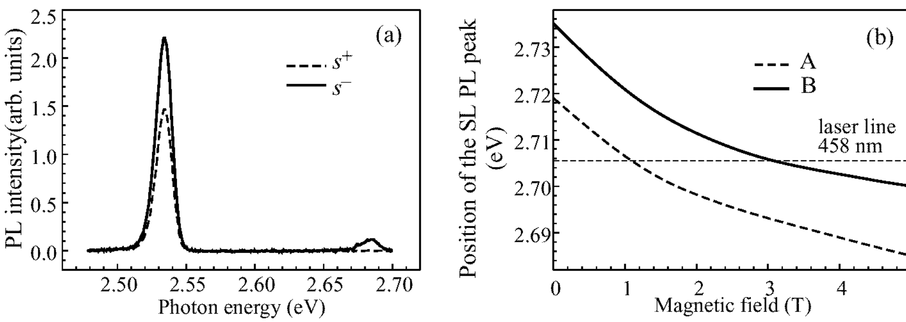

Fig. 2. (a) σ^+ and σ^- PL spectra measured in sample A at 5 T under 458 nm excitation. (b) Energy of the SL PL peak versus magnetic field for samples A (dashed curve) and B (solid curve).

were used for the PL excitation. The PL circular polarization was analyzed using a 1/4 plate followed by a linear polarizer.

Figure 2(a) shows the spectra of σ^+ and σ^- circular polarized PL measured at 5 T in sample A excited by a 458 nm laser line, i.e. above the fundamental band edge of the SL. There are two emission bands visible, attributed to the emission of localized heavy-hole excitons in the SL (2.685 eV) and the SQW (2.534 eV). The SL peak is almost completely σ^+ polarized, starting from small magnetic fields less than 1 T. Figure 2(b) demonstrates the SL PL peak energy versus magnetic field for both samples. The curves are identical, besides a small energy offset ($\sim$ 15 meV) which is due to a small difference in the nominal thickness of the CdSe layers between the samples. Both the PL shift and polarization are typical for the effect of giant Zeeman splitting of excitons, conventionally observed in Zn(Cd)MnSe based heterostructures [6].

For the SQW emission band, the magnetic-field-induced shift is negligibly small, which is expected for the non-magnetic QW. The dominant effect of the magnetic field is an increase in the PL circular polarization, the sign and the degree of polarization both depending on the wavelength of the exciting light. The polarization degree at the peak maximum versus magnetic field is plotted in Figs. 3(a) and (b) for samples A and B, respectively. The different curves correspond to excitation at 351 nm, 458 nm or 474 nm.

The excitation wavelength 474 nm corresponds to a selective excitation of the SQW, because the photon energy is below the SL band edge. The respective curves (dotted ones in the Figs. 3(a) and (b)) are practically the same for the two samples. The SQW PL in this case is weakly σ^- polarized (less than 10% at 5 T), with the polarization degree depending linearly on the magnetic field. This behavior is in good agreement with recent magneto-absorption measurements of ZnCdSe/ZnSe QWs [7], indicating a positive sign of the excitonic g-factor $g_{ex} = g_h - g_e$, where g_h and g_e are electron and hole g-factors. In this case, the lowest excitonic state in a magnetic field is $|+1/2, -3/2\rangle$, which is active in σ^- polarization. In $|s, m\rangle$ the notation $s(m)$ denotes the projection of the electron spin

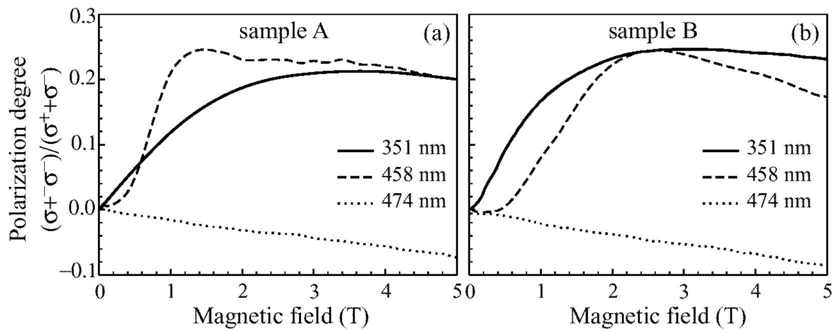

Fig. 3. Degree of circular polarization at the maximum of the SQW PL peak versus magnetic field for samples A (a) and B (b). Different curves correspond to various excitation wavelengths as indicated on the plot.

(hole angular momentum) on the z axis. The scheme of the spin structure of optically active SQW excitons in a magnetic field is shown in Fig. 1.

For the excitation above the SL band edge (351 nm and 458 nm) the SQW PL polarization changes its sign to σ^+. Also the circular polarization degree is noticeably larger in this case, reaching 40% (dashed curve in Fig. 3(a) near 0.8 T). This observation is indicative of efficient injection of spin-polarized electrons and holes from the DMS SL into the non-magnetic QW. Indeed, the lowest exciton in the DMS SL in a magnetic field is $|-1/2, +3/2\rangle$ (see the schematic drawing in Fig. 1). Being injected in the SQW, the $|-1/2\rangle$ electrons and $|+3/2\rangle$ holes contribute to population of the $|-1/2, +3/2\rangle$ excitons in the SQW, which results in the inverted population of the QW excitons and in enhancement of the σ^+ polarized PL. Therefore, the degree of σ^+ polarization of the SQW PL can serve as a measure of the spin injection efficiency.

For the non-resonant excitation (351 nm) the dependence of the polarization degree on magnetic field (solid curves in Figs. 3(a) and (b)) is mainly determined by two competitive factors. Firstly, at relatively small magnetic fields the σ^+ polarization increases due to the increase in the population of the $|-1/2, +3/2\rangle$ excitons in the DMS SL. At larger fields, the increase in the σ^+ polarization saturates due to the saturation behavior of the Brillouin function describing magnetization in DMS [6]. In this region, the dominant factor is an increase in the intrinsic σ^- polarization natural for a non-magnetic ZnCdSe/ZnSe QW. For the resonant excitation close to the SL exciton (458 nm), the degree of circular polarization of the SQW PL peak depends on magnetic field in a more complicated manner. As shown in Fig. 2(b), the SL exciton crosses the excitation energy at magnetic fields near 1 T for sample A and 3 T for sample B. The crossings manifest themselves in a resonant enhancement of the degree of circular polarization of the SQW PL in the vicinity of these fields (see dashed curves in Figs 3(a) and (b)). Note that for sample A the resonance is narrower and better pronounced than that for sample B, which results from larger steepness of the curves in Fig. 2(b) at 1 T and smaller contribution from the intrinsic σ^- polarization of QW excitons at this small magnetic field.

In conclusion, we have reported on a realization of efficient injection of photo-excited carriers, spin-polarized by an external magnetic field, from a DMS ZnMnSe/CdSe SL into a non-magnetic ZnCdSe SQW. A spin injection efficiency of at least 25% has been estimated by monitoring the degree of circular polarization of the QW excitonic PL.

Acknowledgements

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